Towards an Objective Evaluation Layer: EEG-Based Assessment of Cognitive Engagement in AI-supported Immersive Cultural Heritage Experience

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Abstract. This study investigates EEG-based evaluation of immersive VR experiences using a publicly available dataset of 51 participants exposed to visual and audiovisual simulations of the Edzná Maya archaeological site. Frontal theta, occipital alpha, and engagement index (beta / (alpha + theta)) are examined as cognitive engagement markers. The findings provide a neurophysiological baseline for future neuroadaptive AI-driven heritage VR systems.

Keywords: EEG, Immersive VR, Cognitive Engagement, Neuroadaptive Systems, Cultural Heritage.

1 Introduction

Virtual Reality (VR) and Augmented Reality (AR) platforms have recently gained significant attention within the Cultural and Creative Industries (CCI), both from academic research and practical deployment perspectives. These technologies are increasingly used to recreate and present historical environments, typically through visually reconstructed representations of ancient sites, often complemented by auditory elements and, in some cases, multisensory stimuli such as wind or temperature to enhance the sense of immersion (Bekele et al., 2018). Beyond the visual and sensory reconstruction, the effectiveness of such systems critically depends on the integration of coherent and engaging narrative structures. The creation of these multimodal experiences requires substantial creative effort, which is increasingly supported and partially automated through advances in Artificial Intelligence (AI), including generative models for content production (Colucci Cante et al., 2024). However, despite these technological advancements, the evaluation of user experience in VR/AR environments - particularly in terms of cognitive engagement and emotional response - remains a challenging and underexplored problem. In this context, Electroencephalography (EEG) offers a promising avenue for this objective, neurophysiologically grounded assessment of immersive experiences.

While user experience in VR/AR environments is traditionally assessed through subjective measures such as questionnaires, interviews, or behavioral observations, these approaches are inherently limited by user bias, low temporal resolution, and lack of continuous monitoring. In contrast, electroencephalography (EEG) provides a quantitative and time-resolved measurement of brain activity, enabling the objective assessment of cognitive and affective states during immersive interactions. This capability is particularly critical for AI-supported VR systems, where adaptive content generation and personalization require reliable feedback signals that go beyond self-reported user experience. EEG-based measurements offer a direct and continuous indicator for cognitive load, attention, and engagement, making them well-suited for evaluating and optimizing immersive environments in a data-driven manner (Tadayyoni et al., 2024; Gramouseni et al., 2023). Therefore, integrating EEG into the evaluation pipeline of VR systems can provide a more robust and scalable framework for assessing user experience, especially in scenarios where AI-driven components dynamically modify the content or interaction flow, supporting a seamless and personalized user experience without disrupting the narrative flow.

In this study, we investigate the feasibility of EEG-based evaluation of VR systems through empirical analysis of neural responses recorded during immersive interactions. For this purpose we utilized a recently released publicly available dataset comprising EEG recordings and user experience reports from 51 participants exposed to virtual simulations of Edzná, a Mayan archaeological site (Alonso-Valerdi et al., 2025). The dataset includes EEG recordings from three conditions: visual-only, audiovisual, and resting state baseline, collected from museum visitors in a controlled setting. These EEG measures are complemented by post-hoc subjective UX assessments, specifically self-reported stimulation and novelty ratings obtained via the hedonic scales of the User Experience Questionnaire (UEQ) collected after each simulation. Building on this dataset, we focus on identifying neurophysiological markers of cognitive load and user engagement and examine their sensitivity to variations in visual / audio-visual immersive content. While the Edzná dataset utilized in this study consists of non-AI-generated content, it serves as a critical baseline to demonstrate how neurophysiological markers can form an objective evaluation layer, providing the necessary ground truth for future AI-driven systems to adapt immersive experiences in real time.

The rest of the paper is organized as follows. In the second section, we will briefly discuss the literature on EEG-based evaluation of VR-AR systems. The methodological approach will be explained in section three. The numerical results obtained from the Edzna dataset will be represented in section four, and finally conclusion and future studies will be discussed in the last section.

2 Background and Related Work

Traditionally, user experience in virtual environments has been assessed through subjective measures such as questionnaires and behavioral observations. However, these approaches are limited by response biases, low temporal resolution, and their inability to capture continuous cognitive and affective states during immersive interactions (Standen et al., 2023). Objective brain responses, such as EEG, offer an alternative approach, providing non-invasive, real-time measurements of neural activity with high temporal resolution. In previous studies, the integration of EEG with immersive VR systems has been investigated across a wide range of applications, from rehabilitation to cognitive assessment and emotion recognition (Choi et al., 2023). Unlike traditional laboratory paradigms that rely on simplified, static stimuli, immersive VR enables the presentation of dynamic, contextually rich environments while maintaining experimental control, making it particularly suitable for neurophysiological investigation (Hofmann et al., 2021).

The results based on previous research suggest that immersive VR results in stronger and more distinctive neural responses compared to non-immersive, two-dimensional displays. Petukhov et al. (2020) demonstrated that EEG patterns recorded during immersive VR skiing was similar to those observed in real-world skiing, where two-dimensional desktop simulations failed to reproduce such neural responses. These findings demonstrated that immersive VR is capable of evoking brain responses that closely mirror those occurring in real-life conditions. Similarly, Hofmann et al. (2021) confirmed a negative association between parieto-occipital alpha power and subjective emotional arousal during an immersive VR rollercoaster experience, demonstrating that EEG can capture emotional dynamics in real-world-like settings. Langiulli et al. (2023) further showed that surround sound presentation in cinematic environments evoked significantly greater event-related desynchronization (ERD) in centro-parietal alpha and low-beta bands compared to conditions where sound was delivered through a single channel, indicating that spatially rich audio enhances immersion in the presented scene. These findings indicate that the degree of immersion directly modulates the neurophysiological correlates of presence and engagement, producing stronger and distinct EEG responses.

The identification of reliable EEG biomarkers for cognitive load and user engagement is the main challenge in this field since brain signals are highly sensitive to individual differences, task demands, and the characteristics of the virtual environment. Regarding cognitive processing, frontal theta power and the engagement index (frontal beta / (frontal alpha + frontal theta)) is widely used as a robust indicator of mental effort and prefrontal engagement. Baceviciute et al. (2021) observed increased theta and decreased alpha and beta power during VR-based reading compared to physical reading, suggesting a deeper memory encoding and greater cognitive demand in immersive environments. Wang et al. (2023) similarly reported increased theta, beta, and gamma activity along with decreased alpha in a VR-based creative design task, reflecting increased attention. Tadayyoni et al. (2024) further demonstrated that frontal and parietal beta and theta features achieved classification accuracies of 86-97% in discriminating cognitive states during VR puzzle-solving using machine learning approaches. With respect to visual processing, occipital alpha power has been consistently linked to visual cortex engagement, with lower alpha values reflecting greater visual processing activity (Esteves et al., 2025; Hofmann et al., 2021).

However, despite growing interest in this area, the use of EEG to assess user experience in culturally and historically immersive VR environments, such as archaeological site reconstructions, has received limited attention. Moreover, most of the existing studies have focused on motor rehabilitation, emotion recognition, or generic cognitive tasks, the potential of such neurophysiological measures to serve as a baseline for adaptive and AI-driven content generation in heritage VR experiences has yet to be investigated. This study addresses this gap by analyzing EEG recordings from 51 participants exposed to visual and audiovisual simulations of the Edzná Maya archaeological site (Alonso-Valerdi et al., 2025), where frontal theta power, occipital alpha power, and engagement index (beta / (alpha + theta)) are investigated as candidate neurophysiological markers of cognitive workload and user engagement across visual and audiovisual stimulus conditions.

3 Methodology

This section describes the dataset, feature extraction, and statistical analysis approaches used in this study. This evaluation framework is intended to serve as a baseline for future neurophysiological evaluation of adaptive and AI-driven VR systems, as further discussed in Section 3.3.

3.1 Dataset

In this study we used a publicly available EEG dataset comprising recordings from 51 museum visitors (30 female, 21 male; age range: 15–81) exposed to visual and audiovisual simulations of the Edzná Maya archaeological site in Mexico (Alonso-Valerdi et al., 2025). Participants data were recorded under three conditions: a resting state baseline (Baseline), a visual-only VR condition (V), and an audiovisual VR condition (AV), where the order of V and AV was counterbalanced across participants. EEG was recorded using a Unicorn Hybrid Black device (g.TEC) with 8 dry electrodes (Fz, C3, Cz, C4, Pz, PO7, Oz, PO8) with a sampling rate of 250 Hz. Preprocessing was performed in EEGLAB, including bandpass filtering (1–30 Hz), manual removal of corrupted segments, and ICA-based ocular artifact rejection.

3.2 EEG Feature Extraction and Statistical Analysis

Preprocessed data were analyzed in Python (v3.12.7), using standard scientific libraries (SciPy, pingouin, statsmodels) for statistical computation. EEG data were segmented into non-overlapping 2-second epochs, resulting in approximately 20 epochs per subject for Baseline and 140 epochs for V and AV conditions. Spectral power was computed for five frequency bands: delta (1–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma (30–45 Hz). Based on the literature three features were extracted: frontal theta power (Fz, 4–8 Hz) as an index of cognitive load, occipital alpha power (Oz, 8–13 Hz) as a marker of visual cortex engagement, and the engagement index (beta / (alpha + theta)) as a measure of prefrontal engagement. For each subject, epoch-level features were averaged within each condition before statistical testing, yielding one value per subject, per condition. Condition differences were assessed using repeated measures ANOVA, with Greenhouse-Geisser correction applied where sphericity was violated. Significant effects were followed up with pairwise t-tests, and p-values were adjusted for multiple comparisons using FDR correction. Two subjects were excluded from parietal (Pz) alpha analyses due corrupted channels.

3.3 Objective Evaluation Layer for a Neuro-adaptive Immersive Experience

Building upon the evaluation framework established in this study, we propose a second-stage methodology that extends the current static immersive setup toward a neuroadaptive, AI-supported VR system. While the initial phase focuses on defining a neuroscience-informed baseline using non-adaptive archaeological content, this phase aims to operationalize these findings into a closed-loop adaptive environment. In the proposed framework, EEG-derived biomarkers of cognitive and attentional states will be continuously monitored and used to guide the adaptation of immersive content. Specifically, neural markers identified in this study, including cognitive load as reflected by frontal theta power, visual cortex activation as indicated by occipital alpha power, and attentional fatigue as captured by parietal alpha increase over time, can be mapped to system-level adaptation parameters. These parameters may include narrative pacing, visual complexity, auditory intensity, and semantic richness of the presented content. The adaptive mechanism is designed as a modular control loop consisting of three main components: (i) real-time or near real-time EEG signal acquisition and preprocessing, (ii) feature extraction and cognitive-emotional state estimation, and (iii) content adaptation driven by an AI-based storytelling engine. The storytelling module is responsible for generating or selecting narrative elements, visual scenes, and audio cues in a way that aligns with the inferred user state. For instance, elevated cognitive workload may trigger a reduction in narrative complexity or visual density, whereas low engagement levels may lead to the introduction of more stimulating or emotionally rich content.

A key design consideration in this framework is the preservation of immersion. Rather than relying on explicit or intrusive user feedback mechanisms (e.g., questionnaires), the system relies on implicit neurophysiological signals to adapt the experience without interrupting users sense of immersion. This is particularly important for older users, for whom interruptions may negatively affect usability and engagement. The proposed neuroadaptive system is intended to operate in both offline and online modes. In the offline setting, EEG data collected during prior sessions can be used to train personalized or population-level models that inform adaptation strategies. In the online setting, lightweight inference mechanisms can enable near real-time adjustments without imposing excessive computational overhead. Importantly, the methodology introduced in this phase does not depend on a specific dataset or cultural heritage context but rather defines a generalizable framework that can be applied to a wide range of immersive applications. The proposed pipeline connects EEG data acquisition and feature extraction to cognitive state estimation and AI-based content generation, forming a closed-loop neuroadaptive system, as illustrated in Figure 1. Overall, this second-phase methodology transforms the evaluation-driven insights of the current study into an actionable neuroadaptive pipeline, enabling the development of AI-supported VR environments that are dynamically aligned with users' cognitive and emotional states.

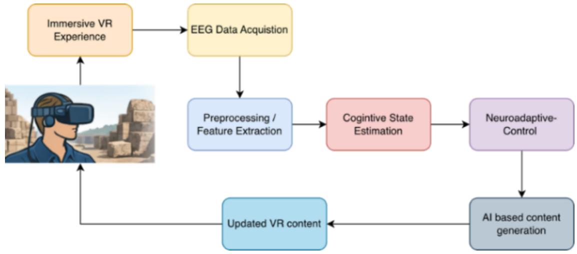

Fig. 1. Proposed neuro-adaptive pipeline.

4 Numerical Results

Table 1 presents the condition means and standard deviations for all targeted features per condition, with a subject-level average. Both frontal theta and occipital alpha power showed a systematic decrease from Baseline to VR conditions, while the engagement index remained relatively consistent across conditions.

Table 1. Condition means and standard deviations for targeted EEG features (based on subject-level averages).

Feature	Baseline (mean ± STD)	V (mean ± STD)	AV (mean ± STD)
Frontal theta (Fz)	0.549 ± 0.484	0.413 ± 0.312	0.340 ± 0.261
Occipital alpha (Oz)	0.527 ± 0.637	0.330 ± 0.307	0.278 ± 0.161
Engagement index (Fz)	0.433 ± 0.214	0.427 ± 0.198	0.402 ± 0.187

Repeated measures ANOVA revealed significant condition effects for occipital alpha ($F(2,90) = 7.778$, $p = 0.004$, $\eta^2 = 0.079$) and frontal theta ($F(2,90) = 4.035$, $p = 0.037$, $\eta^2 = 0.034$), with Greenhouse-Geisser correction applied in both cases due to sphericity violation (Table 2).

Table 2. Repeated measures ANOVA results. GG = Greenhouse-Geisser corrected p-value. η^2 = generalized eta squared. * $p < 0.05$, ** $p < 0.01$.

Feature	F(2,90)	P (uncorr.)	P (GG corr.)	η^2
Occipital alpha	7.778	0.0008	0.0035 **	0.079
Frontal theta	4.035	0.0208	0.0366 *	0.034
Engagement index	1.203	0.3048	0.3019 ns	0.008

Post-hoc pairwise comparisons with FDR correction showed that occipital alpha was significantly lower during both V ($p = 0.015$, $d = 0.40$) and AV ($p = 0.011$, $d = 0.45$) conditions compared to Baseline, indicating visual cortex engagement during VR stimulation. Frontal theta followed a similar trend but did not reach significance in pairwise comparisons after FDR correction. The engagement index did not reach statistical significance across conditions, suggesting that prefrontal engagement may not be sufficiently captured by this measure with the current experimental design. Among the six band power features examined, the most consistent findings were observed at posterior electrode sites. Parietal alpha (Pz) showed the largest effect sizes in the dataset, with significantly lower power during both V ($p = 0.006$, $d = 0.45$) and AV ($p = 0.003$, $d = 0.53$) compared to Baseline. Occipital alpha (Oz) similarly showed significant decrease during both VR conditions. Central alpha (Cz) showed a significant effect for Baseline vs AV ($p = 0.044$, $d = 0.37$) and Baseline vs V did not show significance but had a comparable effect size ($p = 0.060$, $d = 0.31$). Frontal theta, frontal beta, and occipital beta did not reach significance after FDR correction. Overall, decrease in alpha power during VR exposure was more pronounced in posterior regions, with the strongest effects at parietal and occipital sites (see Figure 2; p-values are FDR corrected).

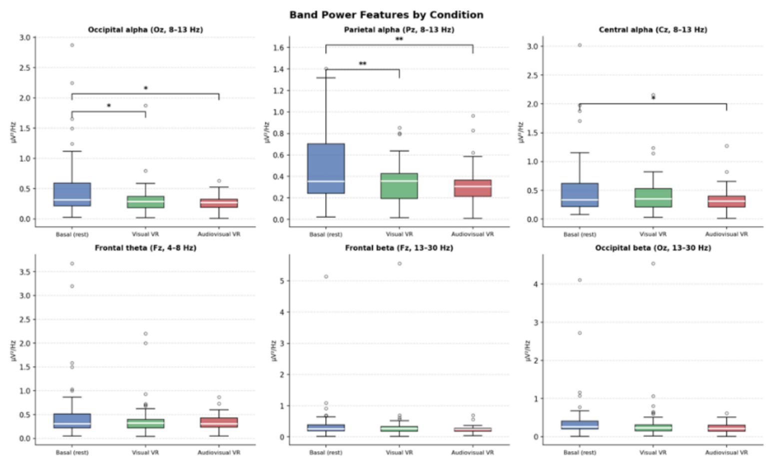

Fig. 2. Band power features across experimental conditions, *p < 0.05, **p < 0.01.

To examine whether engagement of subjects was sustained throughout the VR experience, a within session analysis was conducted by dividing each condition into early, middle, and late temporal thirds where for each condition the total number of epochs were divided into three equal consecutive parts based on their temporal order within the session. Baseline condition showed no significant temporal effects in any feature, serving as a validation that observed changes in VR conditions reflect engagement of subjects rather than signal drift. During Visual VR, occipital alpha increased ($p = 0.035$, $d = 0.32$), frontal theta increased ($p = 0.012$, $d = 0.37$), parietal alpha increased ($p = 0.002$, $d = 0.49$), and the engagement index decreased ($p = 0.045$, $d = 0.29$), collectively indicating progressive disengagement across frontal, occipital, and parietal regions. On the other hand, with Audiovisual VR, while frontal theta, occipital alpha, and the engagement index remained stable throughout the session, suggesting that audio sustained frontal and visual cortical engagement. However, parietal alpha showed the strongest effect in the entire dataset ($p < 0.001$, $d = 0.70$), with an increase 40% larger than Visual condition possibly pointing to an attentional fatigue caused by additional demands of multisensory integration.

Note that, for repeated measures ANOVA, the F-statistic reflects the ratio of between-condition variance to error variance, and generalized eta squared (η^2) is reported as a measure of overall effect size, with values of 0.01, 0.06, and 0.14 indicating small, medium, and large effects, respectively. For pairwise comparisons, Cohen's d is reported alongside p-values as a sample-size independent measure of practical significance, with values of 0.2, 0.5, and 0.8 interpreted as small, medium, and large effects.

5 Discussion

The most consistent finding across all analyses is a robust decrease in alpha power during VR exposure compared to resting state (Baseline), observed at occipital (Oz), parietal (Pz), and central (Cz) electrode sites. This finding is consistent with findings from previous VR-EEG studies reporting alpha suppression under immersive stimulation (Hofmann et al., 2021; Esteves et al., 2025) and is also well-established in the EEG literature where alpha suppression is considered as marker of cortical activation during visual processing. This effect was dominant in posterior regions especially strong at parietal and occipital regions, also aligning with the known role of these regions in visual engagement and sensory processing.

No significant EEG difference was observed between the visual-only and audiovisual conditions at any electrode or frequency band after FDR correction. This absence of a V vs. AV effect may reflect several factors. First, the passive viewing design limits top-down attentional modulation by audio. Second, the 8-channel montage offers limited spatial resolution, which may not be sufficient to capture activity in auditory or multisensory integration regions. Third, alpha power suppression may not be the most sensitive measure for detecting audiovisual integration effects. For instance, gamma band activity and inter-regional connectivity measures have been shown to be more responsive to multisensory binding (Langiulli et al., 2023). Future studies with higher number of electrodes, as well as gamma band and connectivity analyses may be helpful for further detection of differential neural responses between visual and audiovisual heritage VR content.

The within-session fatigue analysis revealed a notable difference between the two VR conditions. While visual VR produced broad fatigue across frontal, occipital, and parietal regions, audiovisual VR preserved frontal and occipital engagement throughout the session. However, parietal alpha showed the strongest fatigue effect in the entire dataset ($d = 0.70$). These findings suggest that while audio helped preserve visual and frontal engagement, it may have also increased the cognitive load associated with processing multiple sensory inputs, leading to faster parietal fatigue. For heritage VR design, this implies that audiovisual content can sustain engagement but should be carefully balanced to avoid overloading the users especially the older adults.

6 Conclusion and Future Work

This study demonstrates that passive VR stimulation produces consistent and significant alpha power suppression at occipital and parietal electrodes compared to resting state, reflecting increased visual cortical engagement. The effect was robust across both visual and audiovisual conditions, with medium effect sizes, and followed a posterior-dominant distribution. Biomarkers, including frontal theta and the engagement index, did not significantly differentiate VR from resting state, possibly due to passive nature of the paradigm. No significant differences were detected between visual and audiovisual conditions, suggesting that the EEG response in this paradigm is driven predominantly by visual stimulation. The within-session fatigue analysis further revealed that audiovisual content preserved frontal and occipital engagement over time, but at the cost of accelerated parietal fatigue, highlighting the importance of cognitive load management in heritage VR design. Together, these findings provide a neurophysiological baseline for EEG-based evaluation of immersive heritage experiences and lay the groundwork for future neuroadaptive VR systems capable of personalizing content based on users real-time cognitive states.

There are several limitations that should be acknowledged; the 8-channel montage restricts spatial resolution and restricted the computation of indices such as frontal alpha asymmetry, limiting the assessment of emotional valence, a dimension especially essential in the proposed neuroadaptive framework. Therefore, the future work should incorporate increased number of electrodes, gamma band and connectivity analyses, as well as affective EEG markers to enable a more complete characterization of user experience during immersive heritage VR. More diverse and higher number of participants would also strengthen the generalizability of the findings.

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